SPECIFICATION

With reference to Publication Number US 2004/0083993 (Application Number 10/691,957), delete Paragraph [0007] and replace with the following new text:

--In U.S. Patent 6,285,151, Wright and Czimmek describe a sensorless "Method of Compensation for Flux Control of an Electromagnetic Actuator." Similar material is described in the 2000 SAE Congress paper 2000-01-1225, "Sensorless Control of Electromagnetic Actuators for Variable Valve Train" by Melbert and Koch. In U.S. Pat. No. 6,657,847, Wright and Czimmek further describe an alternative sensorless "Method of Using Inductance for Determining the Position of an Armature in an Electromagnetic Solenoid," and in U.S. Patent 6,681,728, Peterson, Stefanopoulou, Megli and Haghgooie disclose a similar "Method for Controlling an Electromechanical Actuator for a Fuel Charge Valve."

Both Wright '847 and Haghgooie '728 view the control problem from the standpoint of being in the right place at the right time and each teaches a method of continuously monitoring velocity, position and current together and adjusting drive voltage each time an error is observed. These methods provide empirical formulas for specific points of course correction in the trajectory of a solenoid moving from one latching position to an opposite latching position, with a goal of low-impact landing with simultaneous magnetic latching. Such systems as these provide some measure of control, but less than is needed for a versatile, quiet-running and long-lasting system. In the words of Wright '847: "Generally, PID (proportional, integral, derivative) control systems can only perfectly compensate a linear system with state variables that are not interactive. Electromagnetic actuators are, however, highly non-linear (and) the state variables are highly interactive."

In light of the current invention, these methods warrant detailed discussion.

Concerning time and control, Wright '847 explicitly departs from the PID control methods, stating (column 2, lines 41-65) that "... there is a need for a true multivariate control system capable of controlling all state variables simultaneously and compensating a nonlinear feedback control system." Wright '847 goes on to describe a state space whose dimensions are position, velocity, electrical current and time. As shall be shown, a better selection would be to eliminate the dimension of time altogether and to substitute flux linkage for current, resulting in simpler, more linear relationships and improved system stability.

The special significance of three state space dimensions (as opposed to any other number) is the number of time-integration delays between a control input change and response in position. Starting from a control voltage, current and flux linkage vary as the time integral of voltage, so that's one "delay." Magnetic force and acceleration changes occur with virtually no delay in relation to flux, so the next significant integration delay is going from force and acceleration to velocity. The third integration delay is in going from velocity to position. All solenoids are subject to at least third-order delay. Current controllers can only alter current at rates permitted by their voltage output range. The slew rate for current varies with the maximum volts-per-turn in the winding. Raising the supply voltage calls for higher-voltage transistors and higher instantaneous power capability. Lowering the number of windings causes the solenoid to draw more current, again raising the instantaneous power demand and also increasing power losses from fixed resistances in transistors and circuit board traces. There is a strong economic incentive to design a solenoid system for operation within relatively low slew rate limits. Voltage

limiting in current control systems creates a very difficult slew-rate nonlinearity. Applicant's system will be seen to use pre-planned control trajectories within system voltage limits, avoiding slew by design.

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Considering practical solenoids of the type used to actuate internal combustion engine valves, the spring forces are so high that they easily dominate over the controllable magnetic force across much of the armature's range of travel. As noted in Haghgooie '728, the solenoid controller exerts very low "control authority," caused both by the dominance of the spring force and by the 'open' position of the armature over most of its travel. The solenoid acts primarily as an oscillating spring-mass system whose motion is only under significant controller influence when the armature is very close to one or the other of the two attracting pole faces. Wright '847 states (col. 11, lines 18-22) that "As a rule of thumb, the armature should be close enough to the stator core that the amount of magnetic flux closed through the core is at least equal to the amount of flux that escapes the core."

In fact, it can be shown that in the region between 20% and 80% of full travel, motion is virtually unperturbed by control action and is governed primarily by the simple harmonic motion of the spring/mass system. As a further important consequence, it is virtually impossible for any controller to significantly influence the overall transit time from armature release to armature recapture. By the time an armature arrives at the final 20% region of significant landing control force, it is too far behind or ahead of schedule for correction, unless its initial kinetic energy was virtually unperturbed by variable operating conditions.

Examining Wright '847 in more detail, we find in 130 of Fig. 12 a graph labeled "Soft Landing Position vs. Time." As is clear throughout Wright '847, the armature trajectory is intended to be controlled to track along a single preferred position-versus-time trajectory, such as trajectory 130. Observation, though, shows that in a solenoid system with low control authority, this approach falls short. An armature whose release opens an automotive exhaust valve (for example) will lose energy quickly after release due to a combination of weak magnetic attraction and strong opposing gas forces from out-rushing exhaust. By mid-course, the armature and valve will have a perturbed kinetic energy due to varying launch conditions. No magnetic controller can be expected to cause such variably perturbed trajectories to converge onto a single position-versus-time graph ending at a specific elapsed time after release. Wright '847 calls for the system to do just that. The consequence is that Wright's system can only successfully control armature motions within a very restricted range of energies established shortly after armature release.

As with the teachings of Wright '847, Haghgooie '728 implies a specific, restrictive time schedule for position, as at column 4, lines 20-25: "In each stage in the operation of the closed-loop

controller, the voltage command signal generated by the controller is equal to:

$$\text{Voltage} = K_i(i_{desired}-i_{measured}) + K_x(x_{desired}-x_{measured}) + K_v(v_{desired}-v_{measured})\text{"}$$

The values of three state variables, current, position and velocity, are each subtracted from "desired" control values of current, position and velocity at specific moments in time. Haghgooie '728 describes procedures for a flux initialization stage and for a landing stage, but it makes clear that in both stages, the form of the control equation is the same. Little is said about how said desired values are established, except that closed loop control is employed, that there is a switch from a flux initialization algorithm to a soft landing algorithm, and that (column 4, lines 32-34) "In the preceding equation, K_i, K_x, and K_v are constants that are determined using a known linear quadratic regulator optimization technique (LQR)." There is no discussion of the three "desired" state variables i, x and v, but clearly they are at least functions of time.

Both Wright '847 and Haghgooie '728 rely on a single "desired" path through state space, wherein every position coordinate along that path is a predetermined function of the time dimension. Note that in Wright '847's Figure 12, graph 130 defines a target position versus time for a single trajectory path through state space. Graph 132 in that same figure, plotting velocity as a function of position, is derived from position information that is already fully defined by the positions and slopes of graph 130. These two graphs simply represent different views of a single trajectory through state space, rather than information about two or more trajectories. Note further that the proportional and rate signals represented at 136 and 140 of the figure are used to derive the third dimension of the state space, in this case expressed as a target electric current. Both Wright '847 and Haghgooie '728 describe methods for causing a

servo-controlled trajectory to attempt to track a single, specific target path, itself described as a function of time.

Because inductance places a practical upper limit on the slew rate of the flux linkage curve, and because a solenoid yoke can only attract and cannot repel an approaching armature, there are very restricted options for achieving the simultaneous arrival of flux at its latching value and velocity at a near-zero landing value exactly when the landing position is reached. As shall be made clear, eliminating the time constraint affords a simpler, more effective method for converging to a target strip of trajectories with a finite width in three-dimensional state space. That strip, defined by a collection of known successful trajectories pre-derived from testing or simulation, permits choosing a trajectory most closely aligned with the solenoid's present state, whenever measured, and gradually steering it to a successful landing, thus avoiding flux slew-rate limiting.—